Small Satellites and RPAS in Global-Change Research Summary and Conclusions

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JASON has now conducted two studies on the use of small satellites and remotely-piloted aircraft (RPAs) in global change research, with special reference to the DOE Atmospheric Radiation Measurement (ARM) program and to DARPA's Small Satellite program. The studies centered around meetings, one in January and the other in June, 1991, to which we invited representatives of all areas of the global change program and of the DOD satellite science and technology community. We have already issued a report on the January study. Here we summarize the main themes and results of our Summer Study; the full report will be issued shortly.

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1 SMALL SATELLITES AND RPAs: SUMMARY AND CONCLUSIONS

JASON has now conducted two studies on the use of small satellites and remotely-piloted aircraft (RPAs) in global change research, with special reference to the DOE Atmospheric Radiation Measurement (ARM) program and to DARPA's Small Satellite program. The studies centered around meetings, one in January and the other in June, 1991, to which we invited representatives of all areas of the global change program and of the DOD satellite science and technology community. We have already issued a report on the January study. Here we summarize the main themes and results of our Summer Study; the full report will be issued shortly.

The charge from DOE and DARPA to JASON was, in essence, to elucidate global change science problems that can be answered by small satellites and RPAs; investigate the role of DOD technology in global change research; and (for DARPA) propose small satellite sensor packages which simultaneously address a remote-sensing mission of interest to DOD and a related one of interest in global change science. In addition, we were asked to brief the EOS Engineering Reivew on our findings.

The Winter Study served to introduce people from a variety of technological communities to one another's problems and possible mutual interests. Our report on this study was itself introductory, dealing in broad terms with the technology of RPAs, small satellites, their instrumentation and support hardware, and the scientific issues they could address. It was clear during the Winter Study that the involved communities' knowledge of each other's

needs was not necessarily as great as their interest in each other.

At the Summer Study we found that many of the participants had made progress since the Winter Study and could, for example, make definite and quantitative proposals for small lightweight instruments for RPAs and small satellites. Our Summer Study report in turn deals as quantitatively as we now can with the issues first raised in the Winter Study and their further evolution as of this summer.

1.1 Scientific Scope of the Study

We investigated those parts of global change research which are reasonably-closely connected with the ARM program. This program is devoted to surface-based site studies of cloud and radiation dynamics (with possible aircraft and satellite support, as we discuss in this report), with an eye toward understanding processes and providing input for global circulation models (GCMs). We divide the scientific scope of the study into three areas:

1. Cloud and radiation dynamics, including radiation budgets and cloud radiative feedback processes.

2. Precipitation, water vapor column content and profiles, cloud formation.

3. Upper tropospheric and stratospheric dynamics and constituents, including greenhouse gases, aerosols, and polar stratospheric clouds.

For the most part we will be concerned with studies of the natural environ-

ment, but we also discuss an active modification experiment (sulfur aerosol seeding over the ocean) which could profitably be studied with small satellite and RPA sensors.

1.2 Remotely Piloted Aircraft

We have looked closely at airborne measurements that fit within the scientific scope of our study, such as those required for understanding clouds and the cloud/radiation interaction as part of the ARM program. We find that RPAs could make a vital—perhaps essential—contribution to ARM through continuous measurements above a CART site to obtain accurate vertical profiles of upper tropospheric radiation, water vapor, water droplets, ice particles, aerosols, and cloud structure, to complement the surface-based measurements. We also find a compelling case for using RPAs to study ozone depletion in the stratosphere.

Why should RPAs be used instead of ordinary aircraft for the measurements we are considering? There are great potential advantages relating to: cost, endurance aloft, altitude ceiling, and pilot safety. It is important to note that these potentialities have not been fully realized, but the technology to turn them into realities seems to be mainly straightforward and near-term. The significant issues that still remain unresolved are: high altitude reciprocating-engine development, RPA crash rate, and FAA approval for flights in the US. In addition, since economics heavily favors small RPAs (at least in the near future), light-weight science instrumentation must be developed, especially for the visible and IR radiation measurements. We discuss all these questions in the subsections below.

1.2.1 Potential Advantages of RPAs

RPAs have benefited from advances during the past decade in design codes (for operating at ceiling between stall and Mach divergence), strong and light composite structures, turbocharged engines, and miniaturization of control systems, giving such aircraft important advantages for global change research:

1. Cost. Economically, small RPAs are the only potentially feasible possibility for nearly continuous airborne measurements within ARM, the more so if two or more aircraft are to be flown simultaneously for accurate radiation divergence measurements. The operating costs for the manned higher altitude research aircraft currently in use or planned (ER-2, Sabreliner, WB 57F) average over $4000/hr, far too expensive for a complete ARM mission. The vendors of small RPAs with performance suitable for ARM suggest RPA acquisition costs of $1M or less, and hourly operating costs of $500/hr. Of course, it remains to be seen whether these costs can actually be realized. Uncertainties in high-altitude engine development and especially in RPA crash rate (each discussed in Section 1.2.2 below) affect any overall cost estimate.

   Aurora's estimate of $20M–$25M total cost, exclusive of scientific instrumentation, for a 5-year ARM program using a Perseus B system seems reasonable enough for the assumptions they made: a range of loss rates up to 1 every 200 missions, no expensive developmental problems with the high altitude engine, and one aircraft aloft continuously. Flying two or more aircraft together for radiation divergence measurements would of course either add to the cost or subtract from

the fraction of time covered. To this estimate must be added the total cost of the instrumentation, including the instrument-loss appropriate for a given RPA crash rate.

2. Endurance Aloft. RPAs can fly for 24 hours at a time or longer. A diurnal cycle of actual measurement time is necessary for most missions. As just one example, changes in cirrus clouds between day and night are important for the radiation budget but have not been measured yet.

3. Altitude. RPAs are expected to operate at higher altitudes ($> 20\,\mathrm{km}$) than manned aircraft, which is crucial for studying ozone depletion and other stratospheric processes. To be useful for ARM they need operate only in the upper troposphere, from about 8 to 18 km, though only one RPA (the Boeing Condor, which is huge and very expensive) has actually done this yet.

4. Pilot Safety. RPAs eliminate the issue of pilot risk, which otherwise can complicate or prevent extended or dangerous oceanic, polar, or night flights. Missions with risk of RPA loss at the level of one per 500 or 1000 flights can be tolerated economically, but such risk is far too high when a pilot's life is involved.

1.2.2 Issues to be Resolved

RPAs certainly hold much promise, but there remain important uncertainties affecting their cost and utility:

1. High Altitude Engine. The Amber aircraft have been tested up to about 8 km, but the performance of light RPAs at higher altitudes is not yet validated. It is straightforward and cheap to build a high-altitude airframe for a small RPA, and the existing avionics—which is an expensive part of an RPA—can be used with little change. The uncertain part is developing reciprocating engines, either multiply turbocharged or carrying onboard oxidizers. The recirculating engine now under construction for operation at stratospheric altitudes onboard Perseus A will be tested soon. The airbreathing, doubly turbocharged engines currently under consideration for ARM, which must operate over a wide range of pressure differentials up through the troposphere, remain to be developed.

2. Crash Rate. RPAs have a history of much higher crash rates than manned aircraft. The RPAs envisioned here could follow flight paths that avoid weather hazards and should have sufficient endurance (> 40 hours) to carry out a diurnal mission and still remain at high altitudes when necessary to ride out storms. At an ARM site in the western US it should be possible to operate takeoff and landing between storms, and maintain nearly continuous measurement time aloft. Nevertheless, we find it difficult to predict the crash rate in advance of some operational flight tests.

3. FAA Approval. Such approval will be required for flights above the US ARM site, or an expensive manned chase aircraft may be required at some altitudes. Developing safe protocols for assuring flight safety without any manned aircraft seems possible, but remains an unresolved issue.

1.2.3 Instrumentation and Measurement Requirements

A 100-200 kg instrument package must be developed for a complete set of measurements for ARM. The standard PMS instruments should be adequate for *in situ* droplet and ice particle sampling. The 60-foot wingspan and light weight of the proposed Perseus B or Gnat 750-93L permit speeds as low as 80 m/s at upper troposphere altitudes, which are slow enough for accurate sampling of sub-100 μm particles (a major difficulty with the high speeds of the manned aircraft now in use). A reliable measure of the total H_2O content is also necessary. If the Lyman α photofragmentation technique proves inadequate, one might consider microwave sounding (perhaps in conjunction with a ground-based transmitter).

The visible/IR instruments could utilize recent improvements in detector technology, focal plane arrays, and miniaturization of support hardware, and have the potential for also meeting requirements of small satellites for instruments of similar weight and capability. The proposal from the combined DOE Labs (radiometer, multispectral imager, camera, and lidar) is a promising first step in such a design. For high precision radiance measurements, position and pointing accuracy become important. To meet these requirements it should be sufficient to locate the position of the RPAs within

100 m by GPS and to mount the radiometers on gimbals and point them to within 10^{-2} rad with compact IMUs.

Assuming RPAs were to be deployed, we have investigated using them for some possible active experiments such as seeding a local ARM site with sulfides and/or oxidants, and detecting the effects on cloud droplets and albedo with the RPAs. Distributing about a ton of sulfur in one week within a 20-km region would suffice to study the details of the aerosol/droplet process.

Higher altitude (20-30 km) RPAs would be the best platforms for studying the mechanism of ozone depletion and other processes in the stratosphere. One essential task is to study the chemistry and transport of Cl and N, and the formation of polar stratospheric clouds in the northern hemisphere that could lead to an Arctic ozone hole similar to the Antarctic hole if greenhouse gases begin to cool the stratosphere. It might be possible to combine important stratospheric and tropospheric missions of RPAs at the proposed Arctic ARM site.

In comparing RPAs with small satellites, we note that even though some instruments may have much in common, there is a great difference betweeen the cost of a small satellite program and an RPA program. Moreover, as described above, RPAs add crucially to the ARM program, making measurements at altitudes beyond the range of the surface-based ARM remote sensors. Many of these measurements cannot be made from satellites. For these reasons, RPAs should have priority over small satellites in the ARM program.

1.3 Small Satellites

Satellites of all size will continue to be the major sensor platforms for many global change missions within the scope of our study, and as such are important to ARM. However, for a number of reasons the time is ripe to develop several small satellites for cloud, radiation, and other atmospheric studies, and we will discuss these independently of their direct connection to ARM. It is unlikely in any case that the ARM program, even with an augmented budget, would allow for the full development of a small satellite program, but ARM could contribute much by, e.g., supporting the development of small lightweight instruments.

We also address the DARPA charge to JASON to propose small-satellite concepts for joint tactical surveillance and global-change missions.

1.3.1 Potential Advantages and Disadvantages

Small satellites are interesting because they should allow fast and flexible response to changing requirements and new developments; a smooth budget cycle; and make it possible to field constellations to meet certain coverage requirements. For example, measuring the radiation budget to a precision of $< 1\%$ requires at least three satellites in orbit at the same time for proper diurnal coverage. On the other hand, there may be disadvantages: higher cost per payload pound, because of multiplication of satellite support hardware; and failure to meet simultaneity requirements for numerous instruments to be at the same place at the same time.

Our judgment for satellites is that meeting many of the science needs within the scope of our study (including the need for constellations) can be done with small satellites without violating any fundamental requirements of simultaneity, and that the current and near-term programs for miniaturization of satellite support hardware, such as DARPA's Small Sat program, and of sensors, makes it very attractive to develop a small-satellite program for global change. This, of course, would go well beyond the scope of the ARM program, and participation of agencies such as DARPA would be of material assistance.

1.3.2 Lightweight Support Hardware and Instrumentation

The DARPA Small Sat program has already gone a long way toward developing lightweight satellite support technology, including guidance and control systems; on-board computers; inflatable solar arrays; and a common small-satellite bus. Lightweight support hardware is the way to get a high payload-to-total mass fraction, thus reducing the launch cost per payload pound. DARPA's goal is to push this fraction up to about 0.7, which will be spectacular if it is achieved.

The next step will be to develop lightweight instruments, which is a less well-developed technology thrust. We have looked at several proposals in this direction, including some Livermore-Los Alamos-Sandia concepts for radiometers, imaging IR spectrometers, and lidars and similar ideas for a Livermore Brilliant Eyes small-satellite constellation. For the most part, these and other concepts for lightweight sensors are serious and interesting, and well worth further investigation and selection of some for full-scale engi-

neering design. We have already mentioned that such concepts will also be important in the development of RPAs for global change research.

Current versions of instruments with similar functions, developed by NASA and NOAA, are heavy by comparison. As one example, the MODIS-N imaging IR spectrometer for NASA's EOS-A satellite, which is intended to measure ocean color and other surface properties, and cloud properties as well, weighs 200 kg, while newly proposed imaging spectrometers, designed mainly just for cloud properties, are supposed to be closer to 20 kg. While the NASA/NOAA instruments in most cases have a proven space-flight heritage that the new proposals do not, and there are reasons for the NASA/NOAA sizes and weights, there are no reasons we know of which one could use to dismiss easily the light-weight instrument concepts for scientific missions of great interest, and we urge support for their development. In this connection, one must avoid the trap of obsession with exceedingly small size and weight. The idea is to do one's reasonable best in meeting these goals, and to let the science objectives determine the overall satellite size. There is a lot of room between a Pegasus-class ($\sim$200 kg) payload and a Titan-IV or Shuttle payload ($>$12,000 kg).

1.3.3 Specific Small-Satellite Missions

The specific small-satellite missions we propose, each tied to one element of the science scope defined in Section 1.2 are:

1. Earth Radiation Budget: Includes a radiometer in the NASA CERES class, plus a lightweight imaging IR spectrometer (generically, an IIRS).

CERES itself is not very heavy (80 kg), but requires a co-flying IIRS for cloud information to attain the desired accuracy of $\leq 1\%$, and then only when there are three such satellites in orbit at the same time. The need could be met by a small IIRS with spatial resolution of 1 km, which could weigh less than 30 kg (when scaled to 800 km altitude) according to designs we have seen, allowing a Pegasus-class payload. With accelerated funding for CERES, and development of a suitable lightweight IIRS (possibly within DOE), a mid-decade launch seems possible. This is an important mission for connecting with earlier ERBE data, for laying a baseline for later measurements, and particularly for overlapping with ARM and FIRE; and we urge that a constellation of three satellites be considered for the earliest possible start.

2. Global Humidity and Precipitation: A microwave nadir sounder and an IIRS optimized for this mission should fit in a 200 kg payload, and could measure surface temperature and column-integrated humidity, but would provide only $\pm 50\%$ rainfall accuracy. Better measurement of precipitation requires a rain-radar such as the 400 kg instrument to be tested on aircraft for the tropical rainfall (TRMM) satellite scheduled for 1997, and also planned for the JEOS satellite. We believe small satellites have a future role to play here, building on what is learned during TRMM and providing sufficient coverage for complete tropical and possibly global precipitation, now one of the major unknowns in global science. The exact size of satellites for this mission depends upon progress in developing small radars.

3. Satellite Limb-Scanning: Includes an IR (and possibly also a microwave) limb sounder; an IIRS optimized for limb viewing; possibly solar/lunar occultation limb scanners, a solar irradiance monitor. Polarimetry

would be useful for aerosols.

We also discuss in the main text the possiblities for lightweight lidars and radars, including synthetic-aperture radars (SARs), which have many global-change applications.

1.4 A DARPA Joint Global Change/Surveillance Satellite

DARPA requested JASON to come up with some concepts for such a satellite, and has proposed one of its own which we will discuss later. Before going into our concepts, we note that the spatial and spectral resolution requirements of passive sensors, and the power requirements for, e.g., lidars, are generally rather different for global change research and for surveillance. As an example, one might want spatial resolution as fine as 1 m for surveillance, while anything finer than 250 m or even 1 km is not needed for global change. Conversely, good spectral resolution ($\Delta\lambda/\lambda \sim 10^{-2}$) and carefully-calibrated precision might be needed for science, but not for surveillance.

1.4.1 Visible/IR Cloud, Radiation, and Surveillance

(This is the area in which DARPA has also made a proposal; ours was developed independently of theirs.) The main sensors are a visible CCD focal-plane array (FPA) with 30-cm optics aperture, capable of 1 m resolution from low-earth orbit (LEO); and an IR bolometer FPA of the type

described in Section 1.5 below, say of size 512 × 512 and capable of $\lesssim 100$ μrad resolution. Adequate spectral resolving power for global change could be gotten with a circular variable filter or linear wedge filter, or even a Michelson interferometer if necessary. The IR FPA would be used as a multi-pixel array for high spatial resolution and low spectral resolution, but could be used as a single- (or few-) pixel detector for the converse conditions. The main aperture would scan to arrive at a desired swath coverage.

1.4.2 Dual-Purpose Lidar

DARPA and ONR are working on a small-satellite-mounted Nd:YAG lidar, to be used for ocean-surface observation for a classified purpose. The needed lidar is quite powerful, and only runs on a 5% duty cycle (using solar arrays and batteries). ONR proposes to run the lidar at its fundamental wavelength of 1.06 μm with a silicon CCD array, but it is probably just as good to double the laser, in part because of the much greater quantum efficiency of silicon at 0.53 μm. The same lidar, run at $\sim$ 0.1 mJ/pulse at 40 Hz, with frequency-doubling and perhaps tripling, would be very useful in global change research for measuring cloud heights and structure; ice sheet height; and properties of atmospheric aerosols (cf. the NASA instrument SWIRLS, proposed for EOS-B). We propose, therefore, that the DARPA-ONR lidar be capable of dual-power operation, presumably by adjustment of the diode laser pumping power, and that it would then serve usefully its surveillance function as well as atmospheric and earth-sensing functions.

1.5 Role of DOD Science and Technology

Various DOD agencies and services, including DARPA, SDIO, the Army and Air Force, have an increasing interest in and commitment to both small-satellite technology and to sensors which might play a role in global change research. We have already mentioned a number of examples: the DARPA Small-Sat program, lidars, small SARS, IR FPAs. These last are being developed for the Army as tactical night-vision sensors, but have a good potential for use in global change research; they consist of large numbers of, e.g., vanadium-oxide bolometers some 50 μm square on a silicon chip. Their detectivity and FPA uniformity are in a range of interest for climate research.

While small-satellite support hardware is of immediate use for global-change satellites, and is rather near-term technology for the most part, the requirements for DOD sensors are different from those used for global change. For example, DOD needs passive IR sensors for space use that look at small 300°K bodies in a few spectral bands against a space background or high limb, or at thrusting boosters; or for tactical (i.e., background-limited) night-vision sensors with good spatial resolution, low or no spectral resolution, with good but not exceptional ($< 1\%$) pixel uniformity. There is some need for calibration, but not at the level ($< 1\%$) needed for the radiation budget. (However, at least one spectrometer designed for space viewing with a circular variable filter has been calibrated to an absolute accuracy of $\sim 2\%$ against a blackbody from 5 to 24 μm.) As a result, there are no DOD instruments which can be directly used in global change research, with its emphasis on spectral resolving power and calibrated precision, and lack of interest in high spatial resolution. Nor, in fact, are many of the current DOD sensors made

to be especially small and light.

Nonetheless, there is much of value in current DOD sensor and small-satellite technology that can be transferred to the global-change community, and, as we have said, increasing interest in participating in the global-change mission through such vehicles as SERDP (Strategic Environmental Research and Development Program). Unfortunately, the past and current level of effort in this technology transfer is too small to be successful, and should be increased substantially, both on the part of DOD and non-DOD agencies. One still finds that the two sides misunderstand one another; for example, there is a certain resistance on the part of the NASA-oriented research community to the thought of multi-pixel (let alone full focal-plane) arrays, in part for reasons of unacceptable non-uniformity and need for individual pixel calibration, although multiple pixels (not necessarily a full FPA) are certainly very helpful in evaluating radiation measurements. On the other hand, for the DOD community to argue for full FPAs without meeting the requirements of pixel uniformity and precision would not be helpful. There is much room for fruitful compromise here, either with dual-use FPAs (see point 1.4 above), or with multi-pixel arrays that do not contain many thousands of detectors, each one of which must be individually calibrated, but perhaps only a few dozen.

1.6 Recommendations

1. Lightweight instruments and support hardware may be essential for the successful use of RPAs and small satellites in global-change research. We recommend that both DOE and DARPA (see point 5 below) sup-

port programs in these areas, with near-term instrument emphasis on cloud and radiation sensors. Other DOD agencies can play vital roles and should be asked to participate at a significant level of effort. These are very appropriate projects for SERDP funding.

2. Development of RPAs and their instruments should be the first priority for augmenting the ARM program. It will also be necessay to construct a comprehensive measurement strategy for RPAs in ARM, including measurement accuracies needed, flight paths, implications for aircraft performance, mix of manned, unmanned aircraft and balloons, and the impact on the ARM plans for data management.

3. Aside from lightweight instruments, it will be necessary to participate in the evolutionary development of RPAs themselves. This includes using existing RPAs, such as Amber, if possible, for mid-altitude tests and missions, and using near-term high-altitude RPAs such as Perseus A for high altitude tests. DOE should participate in support of high-altitude long-endurance engine development, such as a two-stage turbocharged engine.

4. Small satellites are important adjuncts to ARM, and could be essential in carrying out near-term cloud and radiation studies of broader scope. We strongly urge that DOE participate (with other agencies) in fielding by the mid-nineties a fleet of at least three concurrent cloud and radiation satellites, carrying a radiometer (CERES or lightweight follow-on) and a lightweight IR imaging spectrometer. Some of the participating satellites can be already-planned flights with add-on instruments. The goal is to have the satellites in orbit during the ARM measurement period, and to shorten the gap between ERBE cloud/radiation studies and NASA programs of the next century.

5. We recommend that DARPA carry out an engineering and science design study of a small satellite for tactical surveillance, components of which might then be of use for a global change mission. If judged successful, this study should lead to joint DARPA support, with other agencies, of the necessay lightweight instrument and support hardware development. Any satellite launched under this program is likely to have its greatest impact if it is flown while ARM is operating, within the next decade.

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